

Computed Tomography Analysis of Fastrac Composite Thrust Chamber Assemblies

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Abstract

Computed tomography (CT) inspection has been integrated into the production process for NASA's Fastrac composite thrust chamber assemblies (TCAs). CT has been proven to be uniquely qualified to detect the known critical flaw for these nozzles, liner cracks that are adjacent to debonds between the liner and overwrap. CT is also being used as a process monitoring tool through analysis of low density indications in the nozzle overwraps. 3d reconstruction of CT images to produce models of flawed areas is being used to give program engineers better insight into the location and nature of nozzle flaws.

Background

Computed tomography (CT) inspection is becoming a widely accepted and more accessible technology for industrial aerospace applications. At MSFC, CT has been successfully applied to a wide variety of development and flight hardware production programs, the latest of which is the Fastrac nozzle development program.

Fastrac nozzles are constructed from an inner liner of silica phenolic reinforced by an outer overwrap of graphite epoxy. CT is used to detect cracks, delaminations, and irregularities in both materials and to detect open bondline separations between the materials.

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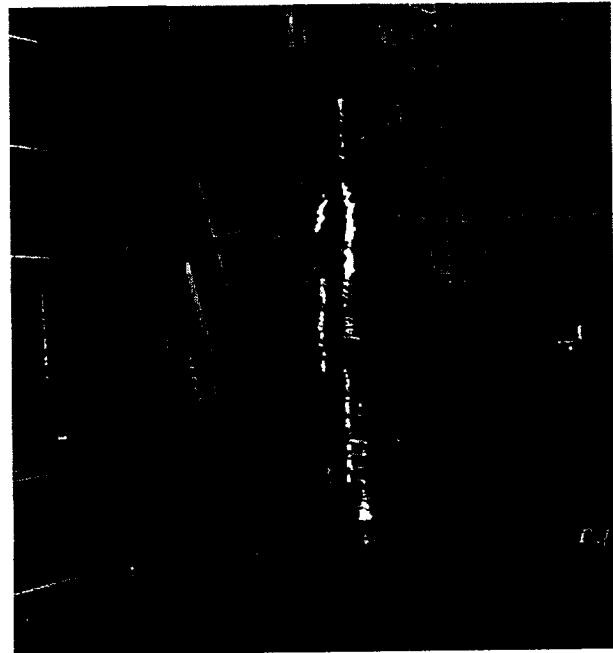


Figure 1. A Fastrac thrust chamber assembly (TCA) mounted on the sample table of the MSFC CT system.

The first significant application of CT to Fastrac nozzles occurred during the investigation of the failure of the 60K-1 development nozzle during static testing. This TCA had been test-fired for 28 seconds on a previous test. During the second test-firing, the nozzle (aft) section of the liner broke free of the TCA and was propelled 300 feet from the test stand 3 seconds after ignition. Pre-fire CT inspection of this TCA had detected debonds in the region of the TCA that failed.

Figure 2. Sketch showing orientation of CT slice planes through a Fastrac TCA.

Post-fire CT images of the remnants of the 60K-1 TCA show a radial crack extending from the liner to near the bondline. This crack was detected in each 6-mm thick CT slice collected at 6-mm intervals perpendicular to the symmetry axis. Both CT and later destructive analysis detected heat-affected material along the walls of the crack, suggesting that the crack existed prior to the failure and was exposed to hot gas during firing. The crack was not detected during visual inspection of the chamber because the surface was obscured.

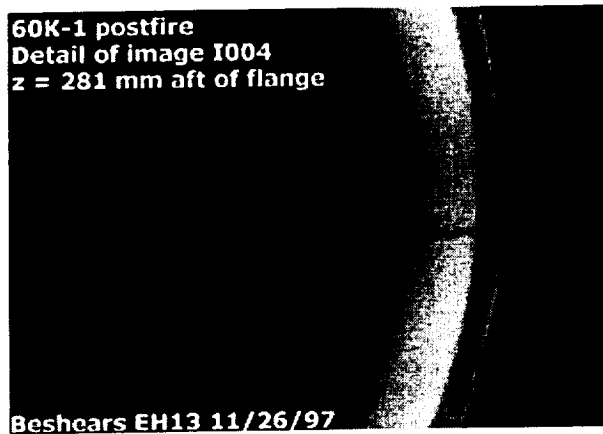


Figure 3. Detail of CT slice of Fastrac TCA 60K-1 remnant, showing crack in liner material extending to bondline.

A 3d model of the TCA fragment was constructed from the CT slices using Noesys[™] and T3D[™] software packages, developed by Fortner Scientific LLC. This model is shown in figure xx. The 3d model can be viewed and sliced open from any angle once constructed, so that features that span multiple CT slices can be seen in a more intuitive fashion, depicted as they actually exist within the geometry of the hardware. As seen in figure 4, the radial crack runs the length of the 60K-1 chamber, from the steel flange insert at the forward end to the failure point. This crack is thought to have been initiated prior to a circumferential delamination in the nozzle liner that occurred adjacent to the known debonds between liner and overwrap. The radial crack and the suspected circumferential delaminations may have been caused by materials and/or manufacturing variations, or by nominal loads induced by multiple firings. The agency investigation board determined that the conjunction of circumferential delaminations in the liner and adjacent bondline separations provides a path for ignition gases to pressurize and rupture the bondline, and is therefore a critical flaw for these nozzles.¹

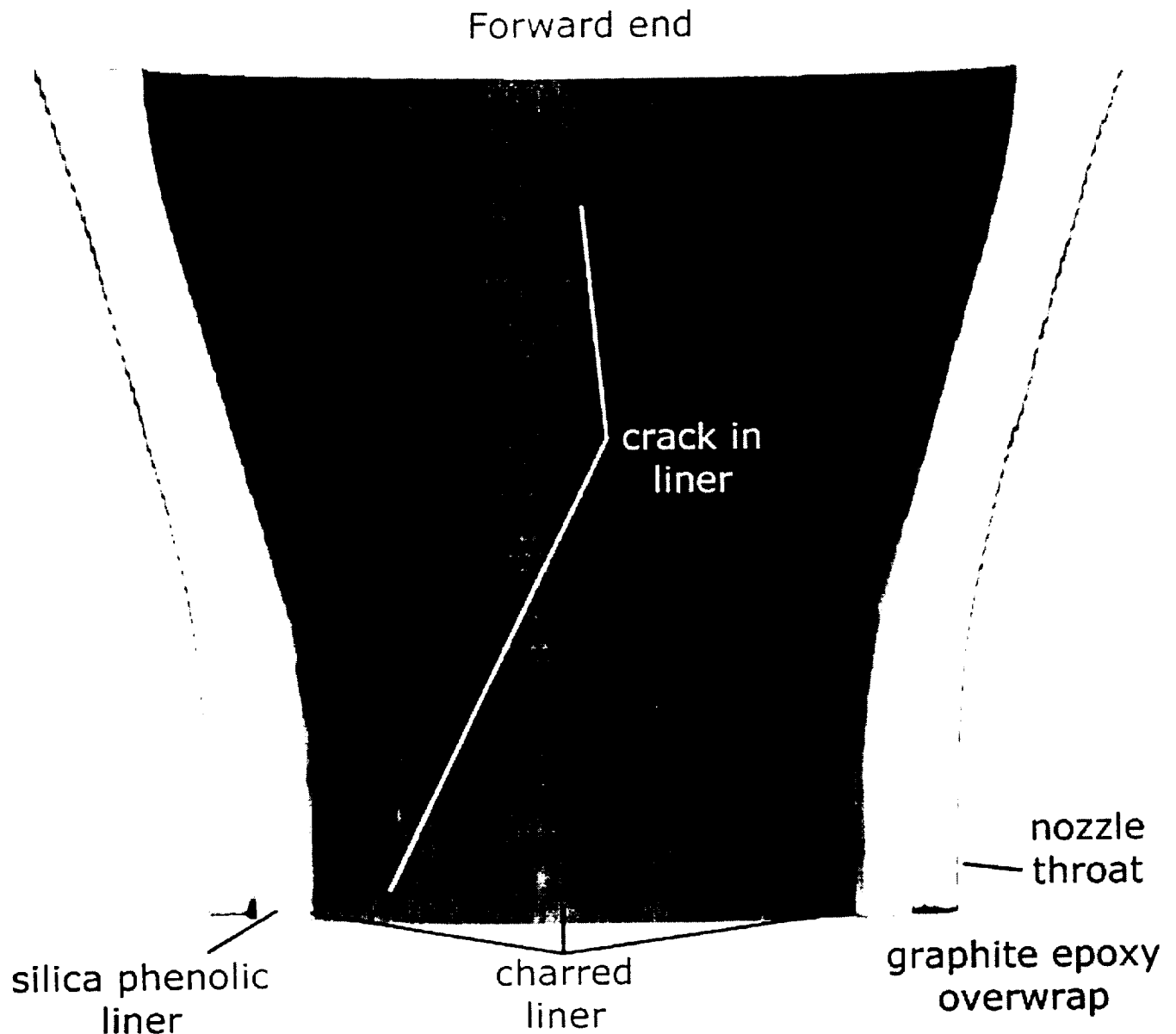


Figure 4. 3d reconstruction of the remnant of Fastrac TCA 60K-1, which was destroyed during testing. CT images revealed the large crack that runs the length of the chamber, which was obscured by char and not visible to the surface.

One unusual aspect of this work has been the detection of low density indications (LDIs) in the graphite epoxy overwrap that tend to form along naturally occurring separations in the graphite fibers.

Application of CT to Fastrac process monitoring and product qualification

Much of the effort in CT inspection of Fastrac TCAs has been focused on detecting known critical conditions as identified above. Another task is helping the designers determine if there are other critical conditions that can be detected by CT or by other available NDE techniques.

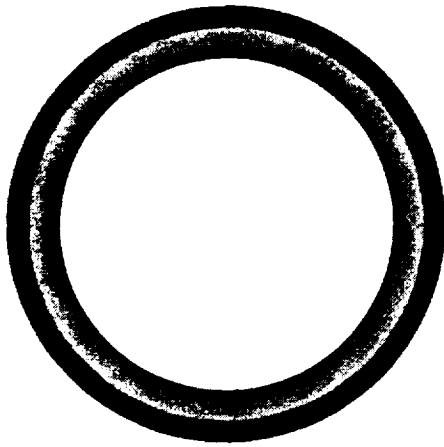
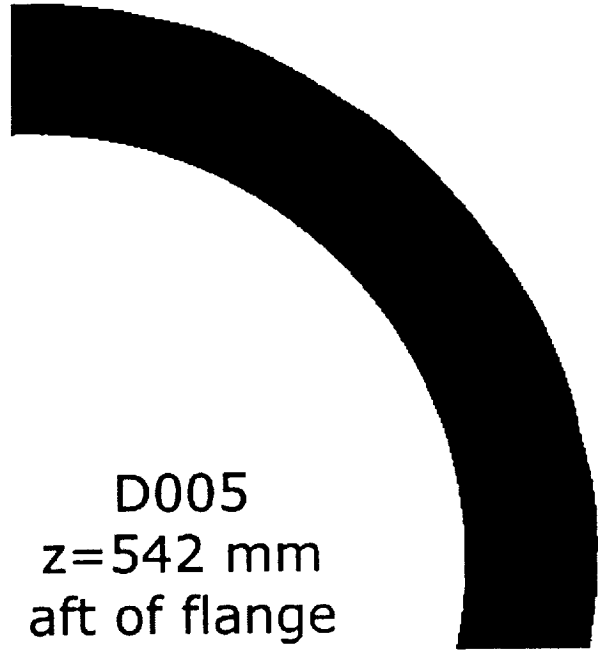


Figure 5. Full CT slice of a Fastrac TCA, showing typical circumferential winding patterns in the overwrap.

These separations (referred to as “winding patterns”) occur immediately forward and aft of the TCA throat, where the contour of the TCA changes rapidly (see figure 1). The separations are sufficiently large to be detected by CT, as shown in figure 5. Low density indications have been detected adjacent to the separations in many nozzles. The LDIs vary in size and density variation from nominal, as shown in figures 6 and 7.



**D005
z=542 mm
aft of flange**

Figure 6. An example of low density indications (LDIs) associated with narrow circumferential winding patterns in the overwrap of a Fastrac TCA



Figure 7. Smaller LDIs associated with winding pattern indications in a different Fastrac TCA.

Using the CT system’s onboard dimensional and density measurement capabilities, we have tracked the sizes and changes in density from surrounding material for a number of nozzles, as shown in Table 1.

Nozzle	LDI volume (mm³)	% density drop
60K-21	522	15.0
60K-23	7462	4.6
60K-25	4075	4.1
60K-26	8200	4.1
60K-27	16665	4.3
60K-29	9994	4.9
60K-34	8399	4.5
60K-35	3964	8.5
60K-38	6490	
60K-39	4000	6.2
60K-40	4000	3.5
60K-41	3975	3.5
60K-42	4370	3.4
60K-43	3118	5.2
60K-44	3134	5.3
60K-46	2158	11.1
60K-47	2124	12.0
60K-48	3938	5.9
60K-49	2524	10.0
60K-50	4645	5.0
60K-51	3016	3.0
60K-52	9690	7.5
60K-53	9002	3.0
60K-54	5249	4.5
Averages	5446	6.0

Table 1. This table shows the volumes of low density indications associated with winding patterns in Fastrac TCAs, as well as the density decrease from nominal surrounding material of the indications.

The data on sizes and relative density changes of low density indications is now being used to track the effects of TCA fabrication process changes. For example, the resin bath used in the filament winding process to produce the overwrap was changed after

TCA 60K-50 was produced. In the next four nozzles, the average density drop is 4.5% from nominal, while the overall average is 6.0%. It appears that the change in resin bath may allow better distribution of resin throughout the overwrap during application, therefore

filling winding pattern spaces more completely and increasing the structural strength of the overwrap.

The sizes of the overwrap LDIs are also being used as an accept/reject criterion for the TCAs. Measurements of the LDIs as they appear on the CT images are currently being compared to the actual sizes

of corresponding features in sectioned TCAs. This effort is very preliminary because few TCAs have yet been released for sectioning after test firing. A comparison of CT indications and the corresponding physical features is shown in figures 8 and 9.

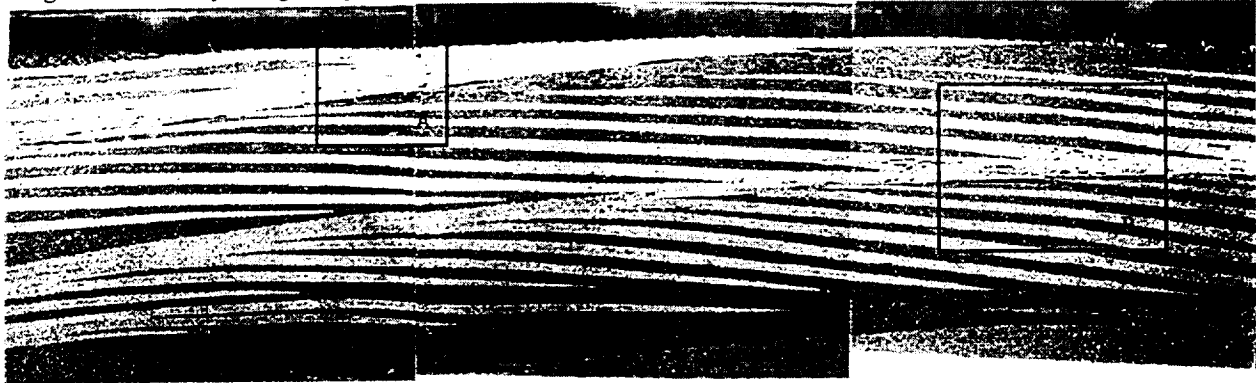
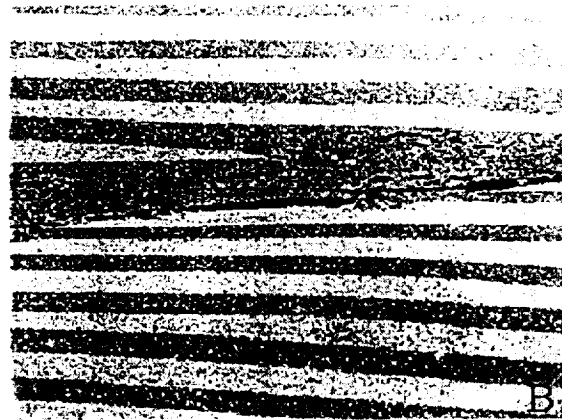


Figure 8. A photograph and 2 microphotographs (below) of a sectioned area of the overwrap of the 60K-21 TCA. The photos show the uneven resin deposits between filament layers in the areas forward and aft of the throat in the TCA, and the voids in those areas.



The photographs in figure 8 show that the areas of uneven resin deposit contain physical voids.²

The corresponding CT low density indications are shown in figure 9.

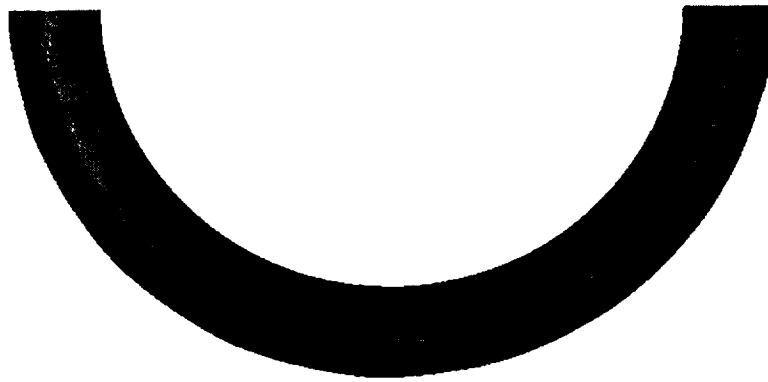


Figure 9. Detail of CT slice of 60K-21 TCA, showing prominent and compact LDIs corresponding to physical voids found after sectioning.

The LDIs in 60K-21 were somewhat more compact than those detected in most other TCAs, with an average volume of 522 mm³, but the density drop for these LDIs was much larger than average at 15.0%. The current allowable maximum volume for overwrap LDIs in production nozzles is set at 522 mm³ because 60K-21 was successfully fired for a full duration (150 sec) test, and there was no change in size or relative density change detected during post-fire CT analysis. This size limit will be reviewed once more TCAs with larger LDI volumes have been successfully fired.

Diagnosis of Critical Flaws in TCAs using CT

As mentioned earlier, investigation of the failure of the 60K-1 TCA determined that the existence of circumferential delaminations in the liner adjacent to debonded areas between the liner and overwrap is a critical flaw for Fastrac TCAs. No such flaws have been detected in manufactured, unfired TCAs, but such flaws have been detected in two TCAs that have been successfully test-fired for full-duration tests.

In an effort to determine performance limits on materials and bondlines, the Fastrac program has attempted multiple firings of nozzles that have completed one full-duration test firing without developing critical flaws. CT is the only inspection method available to us that will detect critical flaws. Figures 10 a-c show three successive slices of 60K-21 post-fire, in which a delamination was detected adjacent to a debond.

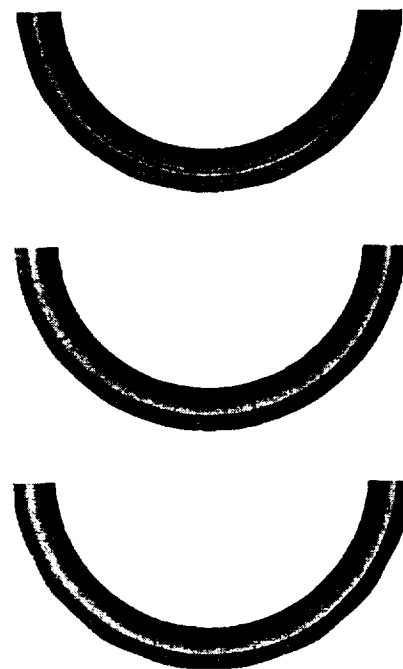


Figure 10a-c. Three consecutive slices from forward moving aft in 60K-21 postfire, showing a liner crack adjacent to a debond.

While it is clear from figure 10 that the liner crack approaches the bondline at a debonded region, it is often more intuitive for our customers if we can present such information in the context of their hardware rather than as ordinary CT slices. An example of this type of presentation is shown in figures 11, 12 and 13.

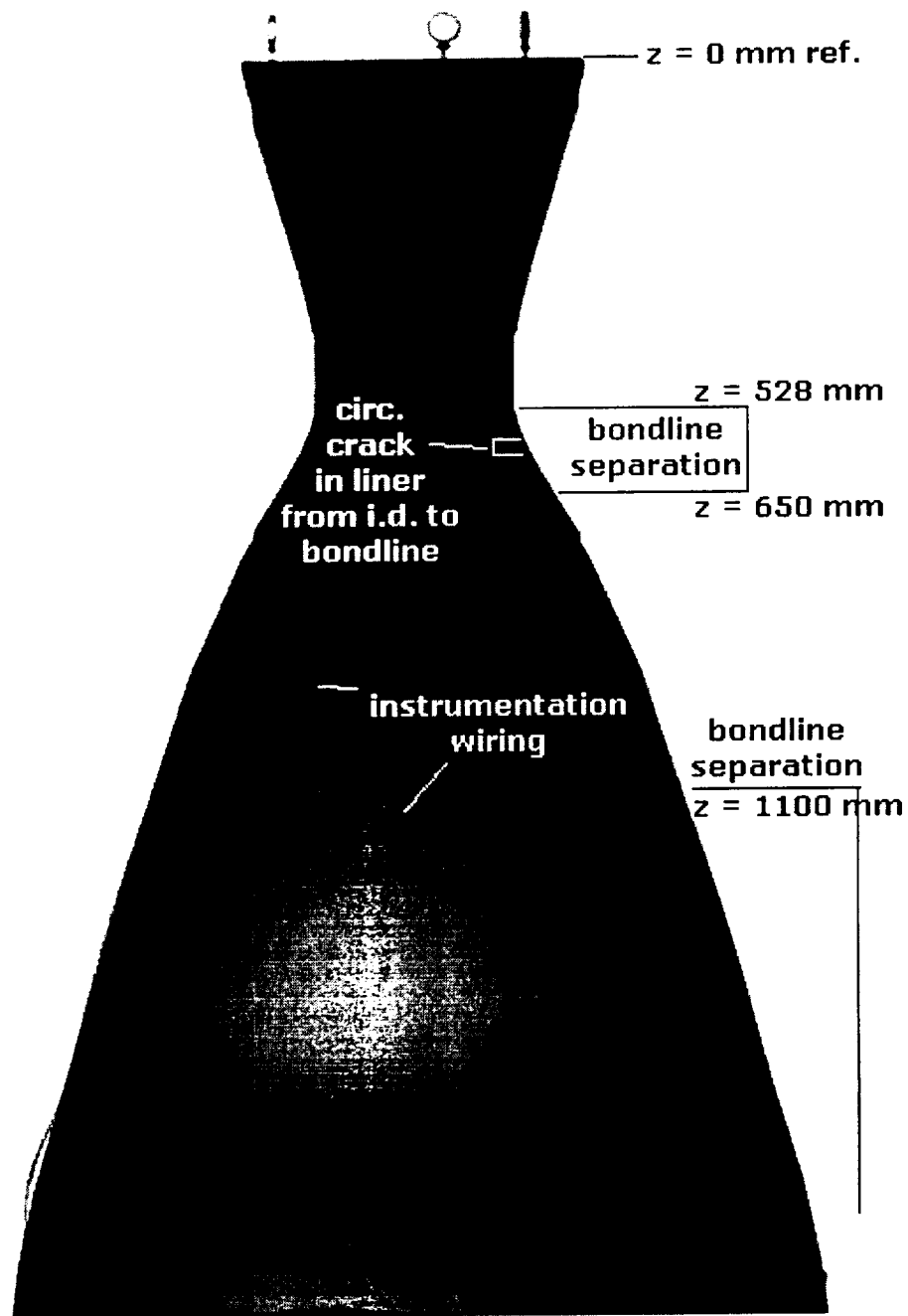
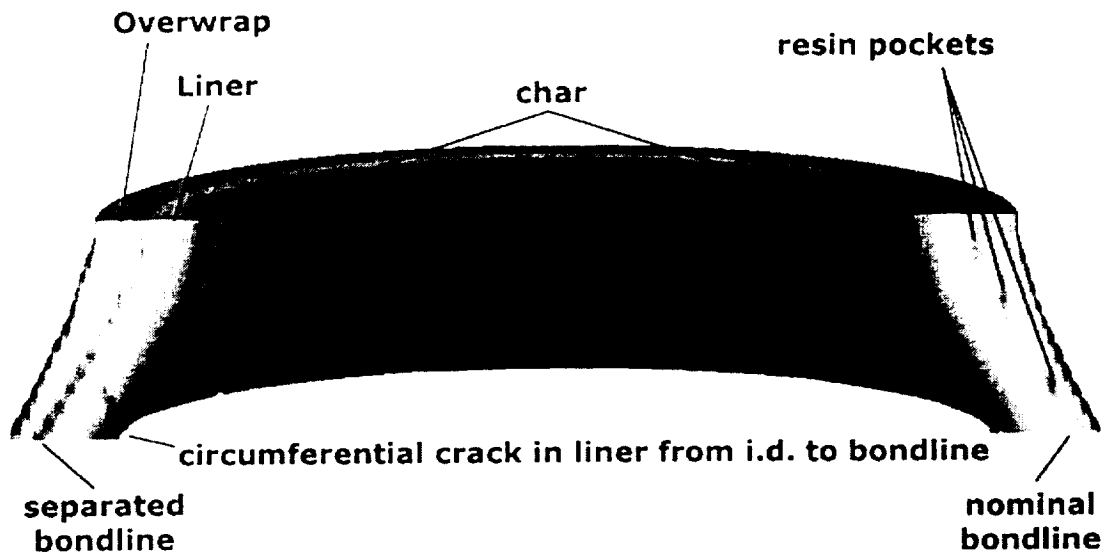


Figure 11. An annotated digital radiograph of 60K-21 postfire, with defect locations marked for presentation to program management.



Fastrac 60K-021 post-fire

MSFC CT Lab

Figure 12. A 3d reconstruction of CT slices from the Fastrac 60K-21 post-fire, showing the location of a critical flaw (delamination adjacent to debond).

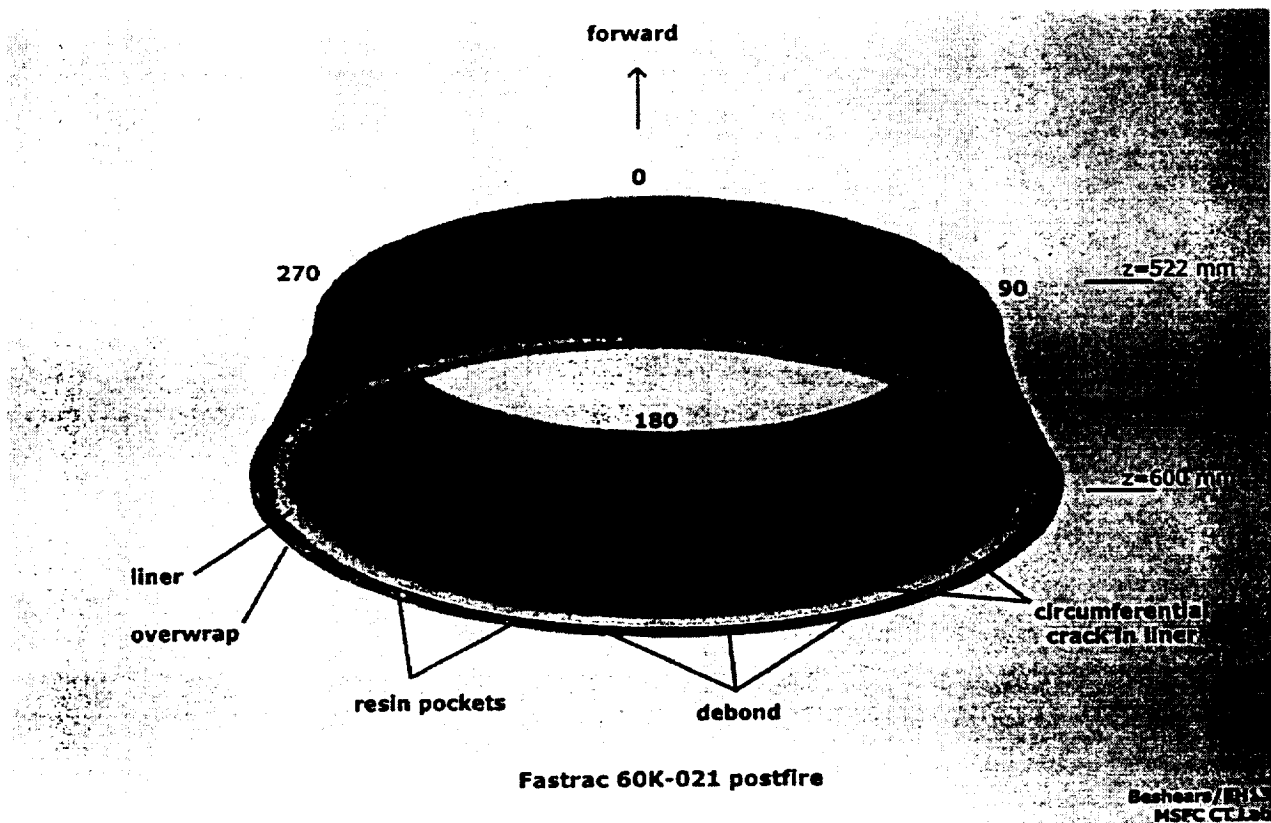


Figure 13. Another view of the 3d reconstruction of 60K-21 postfire, showing the extent of the delamination in the liner. Debonds and winding pattern LDIs are also visible.

As was the case with the crack in 60K-1, the delamination in 60K-21 was not visible on visual inspection even though it was open to the liner i.d. surface, because a heavy layer of charred liner material obscured the opening of the delamination at the surface. Program engineers chose not to fire 60K-21 again based on the results of the CT inspection. A similar finding in the post-fire 60K-17 TCA led to the same decision for that TCA.

Conclusion

Computed tomography inspection has been proven to be an essential technique for the development of Fastrac TCAs for both test and flight articles. We will continue to inspect TCAs for the life of the program, well into 2002, and we will also continue to refine our inspection and visualization techniques to help the program determine and detect critical flaws.

Acknowledgements

Grateful acknowledgements are made to Robert Stowell and David Myers of Lockheed Martin Manned Space Systems, the operators of the MSFC CT system; to J. Dane Garver of MSFC for the CAD drawing of CT slice planes in Fastrac TCAs; and to Dr. Alan Nettles of MSFC for permission to use the photographs of sectioned overwrap.

References

1. Key, C. F., *et al*, "Final Report of the Board of Investigation for the MSFC Fastrac 60K TCA Mishap that Occurred on November 5, 1997".
2. Nettles, Alan, MSFC, personal communication.